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SO_2 pollution of heavy oil-fired steam power plants in Iran

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ABSTRACT

Steam power plants using heavy oil provided about 17.4%, equivalent to 35.49 TWh, of electricity in Iran in 2007. However, having 1.55–3.5 weight percentage of sulfur, heavy oil produces SO_2 pollutant. Utilization of Flue Gas Desulfurization systems (FGD) in Iran's steam power plants is not common and thereby, this pollutant is dispersed in the atmosphere easily. In 2007, the average emission factor of SO_2 pollutant for steam power plants was 15.27 g/kWh, which means regarding the amount of electricity generated by steam power plants using heavy oil, 541,000 Mg of this pollutant was produced. In this study, mass distribution of SO_2 in terms of Mg/yr is considered and dispersion of this pollutant in each of the 16 steam power plants under study is modeled using Atmospheric Dispersion Modeling System (ADMS). Details of this study are demonstrated using Geographical Information System (GIS) software, ArcGIS. Finally, the average emission factor of SO_2 and the emission of it in Iran's steam power plants as well as SO_2 emission reduction programs of this country are compared with their alternatives in Turkey and China.

1. Introduction

Energy is the social and economical growth engine of each country and its generation is considered as a serious challenge especially in developing countries. Electricity generation using fossil fuels has destructive effects on environment. Emission of pollutants such as SO_2 produced by burning fuel oil and coal in power plants has damaged public health, water and forest ecosystem, due to the acidification of soil and lakes (Islas and Grande, 2008).

Sulfur dioxide is a member of a group of highly reactive gasses known as "oxides of sulfur." The largest sources of SO_2 emissions are fossil fuel combustion at power plants (73%) and other industrial facilities (20%). Smaller sources of SO_2 emissions include industrial processes such as extracting metal from ore, and the burning of high sulfur containing fuels by locomotives, large ships and non-road equipments. Emissions that lead to high concentrations of SO_2 generally also lead to the formation of other SO_x. The control measures that reduce SO_2 can generally be expected to reduce people's exposures to all gaseous SO_x. This may have the important co-benefit of reducing the formation of fine sulfate particles, which pose significant public health threats. SO_x can react with other compounds in the atmosphere to form the small particles. These particles penetrate deeply into sensitive parts of the lungs and can cause or worsen respiratory disease, such as emphysema and bronchitis, and can aggravate existing heart disease, leading to increased hospital admissions and premature death (EPA, 2011).

Sulfur oxides are released when fossil fuels such as coal and heavy fuel oil are burned. They mix with the hydrocarbon radicals in the atmosphere and form sulfuric acid. The hydrocarbon radicals may give off an oxygen atom to SO_2 to form SO_3, which in turn is converted to H_2SO_4 droplets resulting in the formation of haze (Rana, 2005). These gaseous emissions can remain in the atmosphere for several days where they can be transported long distances by wind, or they can be scavenged from the atmosphere by rain, snow or fog and deposited to the earth's surface. This phenomenon is referred to as acid rain or, more accurately as acid deposition. The aquatic effects of acid deposition are both chemical and biological. Surface water chemistry can change and become more acidic when exposed to acidic deposition. The underlying geology plays a big role in how sensitive surface waters are to chemical changes from acidic deposition. Materials exposed to the elements will degrade from natural weathering processes. The presence of air pollution and acidic deposition can accelerate the rate of deterioration of certain materials. Materials susceptible to damage include monuments, historic buildings, outdoor structures (such as bridges) and automotive paints and finishes. For some materials, such as carbonate, steel or nickel, the effects are apparent after about one year of exposure. For other materials, including copper and paints, effects may appear after about four years. Research suggests that materials containing calcium carbonate, such as limestone, marble and galvanized steel are particularly sensitive to the effects of acid deposition.

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Links between SO_2 and sulfate aerosols and visibility are indirect, but quite strong. Small particles, such as sulfate aerosols, tend to scatter light and reduce atmospheric visibility (EPA, 2002).

SO_2 emissions from thermal power plants and abatement costs of them were reported in several studies in the countries such as Malaysia, China, India, Mexico, Polish and Turkey (Streets and Waldhoff, 2000; Kaminski, 2003; Islas and Grande, 2008; Reddy and Venkataraman, 2002; Chakraborty et al., 2008; Say, 2006; Vardar and Yumurtaci, 2010; Mahlia, 2002; Zhao et al., 2008; Su et al., 2011).

The emission of SO_2 from large combustion units is proportional to the sulfur content of the fuel and the fuel consumption as well as utilizing emission reduction systems. Containing sulfur and heavy metals, heavy oil is considered as a pollutant producing material. PM and SO_2 generated by heavy oil are more important than other pollutants since they expose habitants of the area to numerous health problems and negative environmental effects, they lead to death in some cases. Therefore, the precise study of emission estimation and dispersion pattern of SO_2 produced by Iran's steam power plants as well as comparing these results with other studies and experiences on SO_2 emission and reduction programs in Turkey (as a neighboring country) and China (as one of the largest electricity markets in the world) are inevitable and vital (Developing Pollutant Map of Iran's Thermal Power Plants, 2008).

Iran, as a developing country, has experienced a considerable industrial growth and population and citizenship increase in the last decade. In addition, electric energy demand in this country has annually increased by 10% during the last 30 years. This demand is expected to encounter an annual 8% growth over the coming years until 2025 (MOE, 2007). Possessing significant fossil fuel resources, Iran enjoyed 10.4% of stabilized crude oil resources and 18.5% of natural gas resources in the world in 2007. Existence of these resources has resulted in utilization of thermal systems for electricity generation in this country, so that near 90% of the required electric energy is produced by thermal power plants. Natural gas (66 %) is the largest source of fuel for electricity generation followed by heavy oil (17.4 %) and gas oil (6.6%) (Energy Balance Book, 2007). Among thermal units of Iran, steams units, with the capacity of 15.6 GW, occupy one third of total power plant installed capacity. In 2007, steam power plants generated 97 TWh of electricity (equivalent to 45% of total electricity generation) (Statistical Book of Iran's Power Industry, 2007).

In Turkey, the most significant development in production was observed in the thermal power plants. In 2009, its share was about 80.3% (155.8 TWh) of total production (194.1 TWh) of the country. Turkey has mainly focused on more usage of natural gas for electricity generation. In 2009, natural gas share was about 48.6% (94.4 TWh) of the total electricity generation in this country. Electricity generation from lignite and coal in Turkey was 55 TWh and share of them in total generated electricity was 28.3 % in 2009. Consumption of lignite for electricity generation was 87% of total lignite production (IEA, 2009a, b).

Air pollution is getting a great environmental concern in Turkey. Air pollution is a result of energy utilization in turkey due to the combustion of coal, lignite, petroleum, natural gas, wood and agricultural wastes. On the other hand, SO_2 emissions have increased rapidly in recent years in Turkey because of the rapid growth of primary energy consumption and increasing use of domestic lignite. The major source of SO_2 emissions is the power sector, contributing more than 50% of the total emissions (Turkey-National study, 2007).

China is the second-largest electricity market in the world, second only to the United States. The excessive usage of fossil fuel in China, which has also sharply increased releases of acid gases such as SO_2 into the atmosphere (U.S. DOE, 2009).Total electricity generation (predominantly coal-fired power plants) was 3695 TWh in 2009. In this year, shares of coal, hydro electric, oil fuel, nuclear energy and natural gas in total electricity generation in China were 78.8%, 16.6%, 0.4 %, 2% and 1.4%, respectively (IEA, 2009a, b).

China has been the largest emitter of SO_2 in the world since 2005, and aggressive deployment of Flue Gas Desulfurization (FGD) at coal-fired power plants appeared in China when this country faced the formidable impact of environmental pollution. From 1990 to 2007, annual SO_2 emission was fluctuated with two peaks (1996 and 2006), and total emission doubled from 15.4 Tg to 30.8 Tg, at an annual growth rate of 4.4% (6.3% since 2000). The total emissions from combustion in 2007 were 28.3 Tg, half of which was contributed by coal-fired power plants. Due to the extensive application of FGD technologies and the phase-out of small, high emitting units, the SO_2 emission began to decrease after 2006 (Su et al., 2011).

2. An overview of current electricity generation condition in Iran

Electricity consumption in Iran has experienced a considerable growth in recent years due to economical development, industrialization and population increase. Electricity generation in Iran in the last years is shown in Fig. 1. In 1973, electric energy generation per capita was 310 kWh, which increased to 2935 kWh in 2008 (Statistical Report on 42 Years of Activities of Iran Electric Power Industry, 2009). Over the last few decades, Iran has confronted two interconnected phenomena: population growth and citizenship increase. These phenomena and their mutual impact have resulted in a high increase in electricity consumption in Iran. Iran's population was equal to 36 million persons in 1973. This amount rose to 73 million persons in 2008, which means the population has doubled over this period (Iran Statistical Year Book, 1973, 2008). Aside from these factors, keeping electricity price reasonable by means of considerable governmental subsides has also affected electricity consumption growth in this country. Electricity consumption growth in the world increases by 3% annually while this amount reaches 8% in Iran (Statistical Report on 42 Years of Activities of Iran Electric Power Industry, 2009). Table 1 represents the distribution of electricity generation by other energy resources in Iran and the world in 2006. As one can see in Table 1, more than two third of electricity consumed in the world is generated by fossil fuels. In Iran, fossil fuels produce approximately 90% of total electric energy. This amount is much higher than its counterparts in OECD and non-OECD countries (IEA, 2006). Meanwhile, 24% of electricity in Iran is generated by oil products including heavy oil

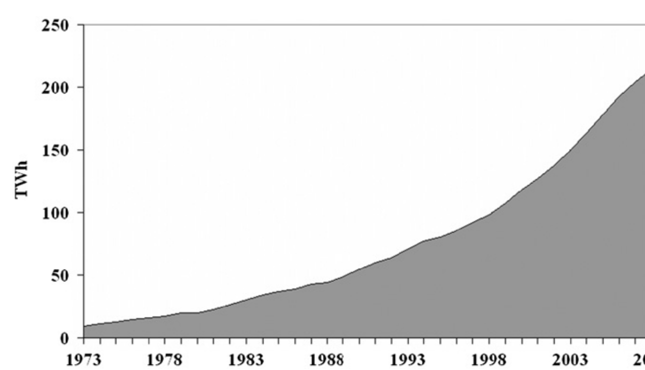

Fig. 1. Electricity generation in Iran from 1973 up to 2008 (adopted from Statistical Report on 42 Years of Activities of Iran Electric Power Industry (2009)).

Table 1
Electric energy generation according to the production method (adopted from IEA (2006)).

	Fossil—fueled power generation (%)				Non fossil—fueled power generation (%)		
	Coal	Oil	Natural gas	Total	Nuclear	Hydro	Other
World	41	5	20	66	15	16.6	2.4
OECD	37.4	3	20	60.4	22.4	12.8	4.6
Non-OECD	46	7.5	20	73.5	5	21.5	0
Iran	0	24	66	90	0	9	1

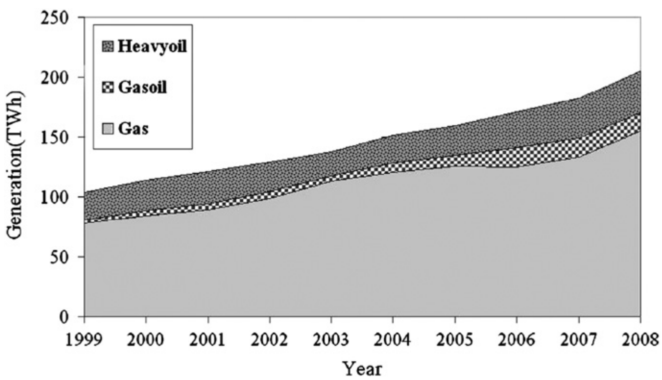

Fig. 2. Distribution of fossil fuels used in electricity generation in Iran from 1999 up to 2008 (adopted from Statistical Report on 42 Years of Activities of Iran Electric Power Industry (2009)).

and gas oil with shares of 17% and 7% sequentially (Energy Balance Book, 2007). Compared to other oil products, natural gas has a higher share in electricity generation. However, in cold seasons with severe frigidity, natural gas is cut from power plants (to be used in residential sector) and thereby, thermal power plants are forced to utilize their secondary fuel, which is either gas oil or heavy oil. In the meantime, in case of intensive temperature reduce (as happened in 2007), gas oil takes a gelatin form and only fuel oil can be utilized. Therefore, other gas turbines and combined cycle power plants of Iran become unusable. In such periods, steam power plants utilizing fuel oil play a critical role in energy generation reliability and operate as the only fossil fuel based resources to provide electricity. Amount of electric energy generated using natural gas, gas oil and heavy oil over the period of 1999 to 2008 is shown in Fig. 2. As one can see, the amount of power generated by natural gas has doubled in the last decade; from 77 TWh in 1999 to 154 TWh in 2008 Meanwhile, fuel oil has perpetually occupied a constant share of electricity generation (about 20%), which is much lower than the share of natural gas (near 70%) (Statistical Report on 42 Years of Activities of Iran Electric Power Industry, 2009).

3. Steam power plants of Iran

In Iran, electric energy is generated by 104 steam, gas turbine, combined cycle, wind and hydroelectric power plants with the total capacity of 47.539 GW, 20 of which are steam power plants with 32% of the total installed capacity. Table 2 represents the installed capacity of Iran's power plants in 2008.General information respecting of electricity generation in Iran's heavy oil-fired steam power plant and fuel oil properties is also provided in Tables 3. Four of the 20 steam power plants of Iran, Tarasht, Loshan, Mashhad and Zargan, do not utilize heavy oil to produce electric energy. The remaining steam power plants use heavy oil

Table 2
Distribution of Iran's total installed power capacity by power plant type in 2008 (adopted from Statistical Book of Iran's Power Industry (2008)).

Type	Installed capacity (GW)	Average efficiency	Share (%)
Steam	15.6	36.3	32
Gas-turbine	12.087	28.9	26
Combined-cycle	11.117	44.5	24
Hydro	8.295	–	17
Diesel oil	0.44	34.4	1

as a secondary fuel. Elin unit of Mashhad power plant is the first steam power plant of Iran, which was operated in 1950 to meet the electricity demand of Mashhad residents. The last steam power plant of Iran was constructed and operated in 2004, when Sahand power plant started operating with 650 MW of capacity (Statistical Book of Iran's Power Industry, 2008).

As represented in Table 3, none of Iran's steam power plants utilizes FGD system and this is one the weak points of these power plants regarding environmental issues. Average sulfur percentage of this fuel is more than 2.5%. Meanwhile, Hamedan and Iranshahr steam power plants with sulfur percentage of more than 3.5% and Tabriz and Bistoon power plants with 1.55% of sulfur percentage have the highest and the least Sulfur amount in turn (Developing Pollutant Map of Iran's Thermal Power Plants, 2008).

In accordance with predefined plans, Energy Ministry of Iran is going to add 4205 MW of capacity to steam power plants of this country until 2014. However, the construction site of only 1280 MW of this capacity has been determined. As planned, Bistoon steam power plant will enjoy 630 MW of capacity increase in 2012 and 2013. In addition, Tabass coal-consuming power plant with the capacity of 650 MW will start operating in 2013. The remaining 1950 MW will be added to the power industry of Iran in 2014. Nevertheless, the construction site of this power plant capacity is yet to be declared (MOE, 2007).

3.1. Heavy oil consumption in Iran's steam power plants and its characteristics

Steam power plants using heavy oil provided about 17.4%, equivalent to 35.49 TWh, of electricity in Iran in 2007. The amount of heavy oil consumption in steam power plants of Iran experienced an increasing trend over the period of 1999 (13,073 TJ) to 2001 (14,949 TJ). Afterwards, it declined due to suitable climatic conditions and acceleration of natural gas extraction projects under operation. In 2003, heavy oil consumption reached its lowest amount, which was 10,857 TJ. In 2007, intense frigidity and natural gas shortage in some areas of Iran resulted in the increase of electricity demand for providing heating and thereby, increase of electricity demand in residential sector and natural gas shortage in the country's power plants, especially gas turbine and combined cycle power plants and also, inactivity. Consequently, heavy oil consumption in steam power plants achieved to the highest amount of it in this year. This increasing trend is still continuing; the consumption of this energy carrier in 2008 was equal to 19,592 TJ (Statistical Report on 42 Years of Activities of Iran Electric Power Industry, 2009).

Regarding the fact that Iran's steam power plants do not utilize SO_2 reduction systems, a considerable amount of this pollutant is produced in these power plants, particularly in cold seasons and this leads to environment pollution. According to the most recent information belonging to the detailed statistics of generation sector of power industry of Iran in 2008, average net calorific value of heavy oil is equal to 43.11 MJ/kg. Sulfur content in this

Table 3
General information about the electricity generation of the existing heavy oil- fired power plants and fuel consumption and properties in 2007 (adopted from Statistical Book of Iran's Power Industry (2008)).

No	Plant's name	Heavy oil consumption in 2007 (1000 m^3)	Installed capacity (MW)	Location	First running date	FGD	Gross production in 2007 (GWh)	Heavy oil net calorific value (MJ/kg)	Sulfur content (%)
1	**Besat**	112	248	Tehran	1967	No	1365	43.09	2.5
2	**Isfehan**	497	835	Isfehan	1969	No	4986	42.40	3.13
3	**Montazarghaem**	495	626	Tehran	1971	No	3478	43.09	2.4
4	**Zarand**	115	40	Kerman	1973	No	296	43.09	3
5	**Neka**	737	1780	Mazandaran	1979	No	10,609	43.09	3
6	**Ramin**	299	1903	Khuzestan	1979	No	10,256	43.09	2.7
7	**Bandarabbas**	668	1280	Hormozgan	1980	No	6681	43.09	3.1
8	**Montazeri**	1456	1600	Isfehan	1984	No	10,735	43.09	3.13
9	**Toos**	187	600	Khorasan Razavi	1985	No	3448	42.19	3
10	**Tabriz**	385	736	Azerbaijan	1986	No	2925	40.59	1.55
11	**Rajaeei**	906	1000	Qazvin	1992	No	6267	43.09	2.6
12	**Bistoon**	367	640	Kermanshah	1994	No	3548	43.99	1.55
13	**Hamedan**	392	1000	Hamedan	1994	No	5092	46.71	3.5
14	**Iranshahr**	589	256	Sistan-Blochestan	1995	No	1756	41.79	3.5
15	**Shazand**	859	1300	Markazi	2000	No	7442	41.49	3.14
16	**Sahand**	371	650	Azerbaijan	2004	No	3724	41.70	3.5

Table 4
Air quality limit values in Iran for SO_2 (adopted from Iran's Department of Environment (2004)).

	Health standard ($\mu g/m^3$)	Welfare standard ($\mu g/m^3$)
Annual	80	60
24-h	365	260
3-h	–	1300

fuel ranges from 1.55% to 3.5% and its special weight is between 920 and 990 kg/m^3 (Developing Pollutant Map of Iran's Thermal Power Plants, 2008).

4. SO_2 emissions from heavy oil-fired steam power plants and Iran's air quality regulations

4.1. Calculation of SO_2 emissions from Iran's steam power plants

In order to determine the emission factor of flue gases such as SO_2 emitted from Iran's thermal power plants, a project entitled "Developing Pollutant Map of Iran's thermal power plant" was accomplished in Environment Protection Department of NRI (Niroo Research Institute) and Research Affair Bureau of Tavanir Company during the years 2007 to 2008. Fifty thermal power plants, consisting of steam, gas-turbine and combined-cycle power plants, with the total installed capacity of 34.863 GW, were studied and investigated (Developing Pollutant Map of Iran's Thermal Power Plants, 2008).

SO_2 concentration is directly measured in terms of ppm by Testo 350 XL flue gas analyzer. Using temperature and static pressure of the stack, this concentration turns into mass concentration in terms of mg/m^3 (Testo Instruments, 2003). Velocity of flue gas (in terms of m/s) is measured by Pitot tube using the flue gas analyzer. Afterwards, flow rate of combustion gases in determined regarding surface area specifications of the stack (Testo Instruments, 2003). Emission rate of SO_2 (in terms of g/s) is then calculated by multiplying flow rate based on m^3/s in SO_2 mass concentration. The SO_2 emissions of heavy oil-fired steam power plants (E_{SO_2}) in terms of g are calculated using emission factor method by (Huang et al., 2011)

$$E_{SO_2} = \sum A \times EF_{SO_2} \times (1-\eta) \quad (1)$$

where A is the activity rate (electricity generation in terms of kWh); EF_{SO_2} is the experimental emission factor of SO_2 in terms of g/kWh; η is the total emission reduction percentage, which is equal to zero if pollution reduction systems are not used. The experimental emission factor of SO_2 for each heavy oil-fired steam power plant is calculated by (Developing Pollutant Map of Iran's Thermal Power Plants, 2008)

$$EF_{SO_2} = \frac{C_{SO_2} \times Q \times 3.6}{kW_e} \quad (2)$$

where C_{SO_2} is the mass concentration of SO_2 in terms of mg/m^3; Q is the flow rate of flue gas based on m^3/s; and kW_e is the power of electricity generation. The average emission factor of SO_2 pollutant in Iran's steam power plants is calculated by (Developing Pollutant Map of Iran's Thermal Power Plants, 2008)

$$Ave(EF_{SO_2}) = \frac{\sum EF_i \times kWh_i}{\sum kWh_i} \quad (3)$$

where $Ave(EF_{SO_2})$ is the equivalent emission factor of SO_2 pollutant in Iran's heavy oil-fired steam power plants; EF_i and kWh_i are the emission factor of SO_2 and electricity generation in each heavy oil-fired steam power plant, respectively. To calculate the total SO_2 emissions, each of heavy oil-fired steam power plants is referred in the appropriate time regarding the fuel exchange from natural gas to heavy oil. In this study, the results of SO_2 measurement in terms of mg/m^3, the flow rate of flue gas based on m^3/s and the power of electricity generation in terms of kW_e are provided and the output of processing (SO_2 emission rate in terms of g/s and emission factor in terms of g/kWh) is calculated for each heavy oil-fired steam power plant in Excel software. SO_2 emissions are then calculated by multiplying SO_2 emission factor based on g/kWh in electricity generation in terms of kWh (Developing Pollutant Map of Iran's Thermal Power Plants, 2008).

4.2. Quality assurance (QA)/quality control activity (QC)

The experimental processes for calculation of SO_2 emissions were undertaken following certain quality assurance (QA) and quality control (QC) documents illustrated in ASTM Standard

Method (ASTM, 2005) and EPA Standard Methods (EPA, 1999). In the present investigation, the following quality control measures were adopted:

1. The flue gas analysis for measurement of SO_2 concentration has been carried out by Air and Physical pollution Reference Laboratory of NRI (Niroo Research Institute). This reference laboratory is accredited by DAP German Accreditation System for Testing, No. DAP-PL-3893.00 (NRI, 2007).
2. The flue gas analyzer (Testo 350 XL) had been calibrated by the SONIMIX 2160 model of Gas Divider Instrument and audit span gas, before measurement process at each heavy oil-fired steam power plant (LN Industries SA, 2008).
3. Sampling points on the stacks of each heavy oil-fired steam power plant were selected according to the procedure used in EPA Standard Methods (EPA, 1999).
4. The flue gas analysis was repeatedly carried out at regular time intervals to check stability in concentration values of SO_2 pollutant. For each heavy oil-fired steam power plant, data processing was carefully checked to find errors if any (EPA, 1999).

4.3. Iran's air quality regulations and power plant emission limit for SO_2

Air quality standards essentially identify levels, with an adequate margin of safety, beyond which a pollutant can cause harm. Ambient standards are concerned with the overall air quality of a community or industrial area and specify allowable pollutant concentrations in such areas. Ambient air quality standards are often subdivided into primary and secondary standards. The primary standards are intended to protect human health and have a margin of safety, whereby economic and technical feasibility are disregarded. Secondary standards refer to environmental effects and are intended to protect overall or long-term human welfare. They pertain to visibility, soil, water, vegetation, domestic animals, wildlife, materials, property, transportation and economic issues. Many countries have set air quality "limit values". These may be presented as national standards or recommended air quality guidelines. Iran has begun to deal with air quality control only recently and does not have national air quality standards. The most comprehensive air quality guideline has been provided by the WHO (World Health Organization) Regional Office for Europe. It provides guideline reference material for 23 air pollution compounds, concentrating on the health effects of those pollutants. For certain pollutants for which there is no threshold below which there are no observable effects, the WHO provides exposure effect information, illustrating the major health impact of different levels of the pollutant. In the developing countries with heavily polluted areas, these guidelines may serve as long-term objectives; however, short-term actions should be guided by a careful analysis of the expected benefits and costs of pollution abatement measures. In practical terms, this leads to temporary, achievable ambient quality objectives. The other valid ambient air quality standard is set by the U.S. Environmental Protection Agency. Some of these standards could be adapted in the developing countries such as Iran (Rostamihozori, 2002).

Iran's air quality regulations were compiled and approved in 1994. According to these regulations; three standards including annual average, maximum 24-h concentration and maximum 3-h concentration were defined for SO_2. In general, Iran's air quality regulations are classified into two sections: primary standard for social health care and secondary standard for social welfare and convenience (Table 4). According to Iran's Department of Environment limit values, valid emission of SO_2 exiting Iran's power plant stacks is equal to 800 ppm equivalent to 1941 mg/Nm^3 (Iran's Department of Environment, 2004).

5. Dispersion modeling of SO_2 emissions from Iran's steam power plants

In this paper, ADMS (Atmospheric Dispersion Modeling System) is used to estimate the dispersion of SO_2 pollutant produced by under-study steam power plants. This software can connect to ArcGIS software. The performance of the model has been evaluated against various measured dispersion data sets (Hanna et al., 2001).

To model SO_2 dispersion by ADMS software, accurate information of emission sources (point sources), surface characteristics, climatic conditions of the under-study region and the modeled area specifications is required. Modeling stages of SO_2 dispersion by ADMS and ArcGIS software is shown in Fig. 3 (ADMS software operation manual, 2004).

5.1. Modeling stages of SO_2 dispersion by ADMS

In the first step of modeling, SO_2 concentration is measured in terms of mg/m^3 and its emission rate in terms of g/s is calculated

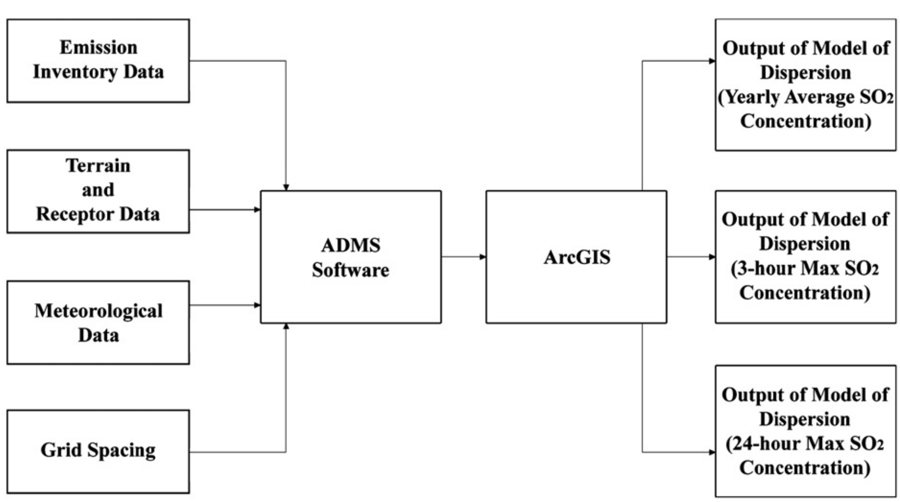

Fig. 3. Modeling stages of SO_2 dispersion by ADMS and ArcGIS software (adopted by ADMS software operation manual (2004)).

using flow rate of flue gas in terms of m^3/s (Developing Pollutant Map of Iran's Thermal Power Plants, 2008). The software is provided with other information including the velocity of combustion gases in terms of m/s, flue gas temperature and ambient temperature in terms of °C, stack height and diameter in terms of meter and geographical position of steam power plants in UTM (Universal Transverse Mercator) coordinate system. Afterwards, using steam power plants activity information, SO_2 pollutant time varying file for each power plant is prepared and given to ADMS software as an input required for the modeling (ADMS software operation manual, 2004).

In the second step of modeling, to apply the influence of surface characteristics, a file with a height point for each 0.72 square kilometers was used, in which the geographical coordinates and height of each point was provided in UTM coordinate system and given to ADMS software. Average climatic information of each day of the year 2007 was also inputted into ADMS software. This information are as follows: day of the year number, hour of the day number, wind speed in terms of m/sec, wind direction in terms of degrees, temperature in terms of degrees of Centigrade, relative humidity (RH%) and cloud covering (Developing Pollutant Map of Iran's Thermal Power Plants, 2008).

Finally, information regarding modeling area and its dimensions and also networking the region is determined in UTM coordinate system. The more the pixels in the network are, the longer the modeling process takes. In this study, a region with 60-kilometer dimensions is considered for each steam power plant. Each side of this square is divided into 30 sections. Thus the whole region contains 900 points. At the end, SO_2 dispersion modeling outputs in annual, 3-h and 24-h forms are demonstrated as colored counters in ArcGIS software (Developing Pollutant Map of Iran's Thermal Power Plants, 2008).

5.2. Model description

ADMS also employs two forms of the concentration equations, depending on the stability conditions. Stability is defined according to the h/L_{MO} classification, where h is the atmospheric boundary layer height (m); and L_{MO} is the Monin–Obukhov length scale (m). The Monin–Obukhov length is defined by (ADMS software operation manual, 2004)

$$L_{MO} = \frac{-u_*^3}{\kappa \times g \times F_{\theta_0}/(\rho \times c_p \times T_0)} \tag{4}$$

in which u_* is the friction velocity at the Earth's surface (m/s); κ (=0.4) is the von Karman constant; g is the acceleration due to gravity (m/s^2); F_{θ_0} is the surface sensible heat flux (W/m^2); ρ and c_P are, respectively, the density (kg/m^3) and specific heat capacity of air (J/kg K); and T_0 is the near surface temperature (K) (ADMS software operation manual, 2004).

For neutral-stable conditions ($h/L_{MO} > 1$) concentration is calculated by Eq. (5). In these conditions, the distribution of concentration profile is a Gaussian plume with reflections at the ground and the inversion layer and ignoring any lower order reflection (ADMS software operation manual, 2004)

$$C\{x,y,z\} = \frac{Q_s}{2\pi U \sigma_y \sigma_z} \times e^{(-y^2/2\sigma_y^2)} \times \left(e^{(-(z-z_s)^2/2\sigma_z^2)} + e^{(-(z+z_s)^2/2\sigma_z^2)} + e^{(-(z+2h-z_s)^2/2\sigma_z^2)} + e^{(-(z-2h+z_s)^2/2\sigma_z^2)} + e^{(-(z-2h-z_s)^2/2\sigma_z^2)}\right) \tag{5}$$

where C is the concentration (g/m^3); Q_s is the pollutant emission rate (g/s); x, y, z is the receptor point; U is the wind speed (m/s); Z_s is the height of source (m); σ_y and σ_z are the horizontal and vertical dispersion parameters (m) (ADMS software operation manual, 2004).

In the connective boundary layer (CBL) the probability distribution of the vertical velocity and, hence, the concentration distribution is non-Gaussian. The concentration is calculated as a weighted sum of two contributions: fistly, C_{CBL}, the value of the concentration per unit source strength from the convective model; and secondly, C_{NBL}, the value of concentration per unit source strength derived from Eq. (5) for the neutral-stable layer. For the transition from CBL to neutral boundary layer (NBL) (defined to be at $h/L_{MO} = -0.3$, say), we let concentration C given by (ADMS software operation manual, 2004)

$$C = Q_s\left[C_{CBL}\left|\frac{h}{L_{MO}}\right| + C_{NBL}\right] \Big/ \left(1 + \left|\frac{h}{L_{MO}}\right|\right). \tag{6}$$

6. Results

6.1. Sulfur dioxide emissions from Iran's heavy oil-fired steam power plants

Due to natural gas pressure fall in cold seasons, Iran's steam power plants are forced to consume heavy oil. Sulfur content of this fuel turns to SO_2 pollutant. Based on the research project, entitled as ''Developing Pollutant Map of Iran's thermal power plant'', accomplished by Environment Department of NRI and Power Research Affair Bureau of Tavanir Company in 2007 and 2008, the concentration of SO_2 exiting steam power plant stacks ranges from 1741 mg/Nm^3 to 4019 mg/Nm^3, depending on the sulfur percentage of heavy oil. Moreover, respecting steam power plants capacity, emission rate and emission factor of this pollutant change in the range of 1201 kg/h to 28,950 kg/h and in the range of 8.19 g/kWh to 26.12 g/kWh, respectively. According to this research, average emission factor of this pollutant (in 2007) in Iran's heavy oil-fired steam power plants is equal to 15.27 g/kWh (Developing Pollutant Map of Iran's Thermal Power Plants, 2008).

Steam power plants of Iran are not equipped with FGD systems to reduce SO_2 emissions, and thereby, the emission factor of this pollutant is only influenced by electricity generation efficiency and sulfur percentage of the consumed heavy oil. Comparing the concentration of SO_2 exiting from steam power plant stacks in Table 5 to valid SO_2 emission amount demonstrates that all steam power plants of Iran, except for Bistoon, exceeds Iran's Department of Environment limits. Mass concentration and emission rate of SO_2 produced by heavy oil consuming steam power plants are represented in Table 5. Fig. 4 shows mass distribution of SO_2

Table 5
SO_2 emission factor, emission rate and mass concentration of it in Iran's heavy oil-fired steam power plants (adopted from Developing Pollutant Map of Iran's Thermal Power Plants (2008).

No	Power plant	SO_2 (mg/Nm^3)	SO_2 (kg/h)	SO_2 (g/kWh)
1	**Besat**	3367	4219	19.82
2	**Isfehan**	2892	11,466	14.14
3	**Montazarghaem**	3353	6886	15.79
4	**Zarand**	3652	1201	26.12
5	**Neka**	3534	22,309	13.94
6	**Ramin**	4019	26,222	16.81
7	**Bandarabbas**	2996	15613	13.01
8	**Montazeri**	3302	28,947	18.09
9	**Toos**	3766	11,170	18.62
10	**Tabriz**	1992	6084	8.95
11	**Rajaeei**	3312	15,973	16.10
12	**Bistoon**	1741	8676	8.19
13	**Hamedan**	3066	7117	14.18
14	**Iranshahr**	4089	5623	23.43
15	**Shazand**	3342	16,398	13.67
16	**Sahand**	2568	4471	14.91

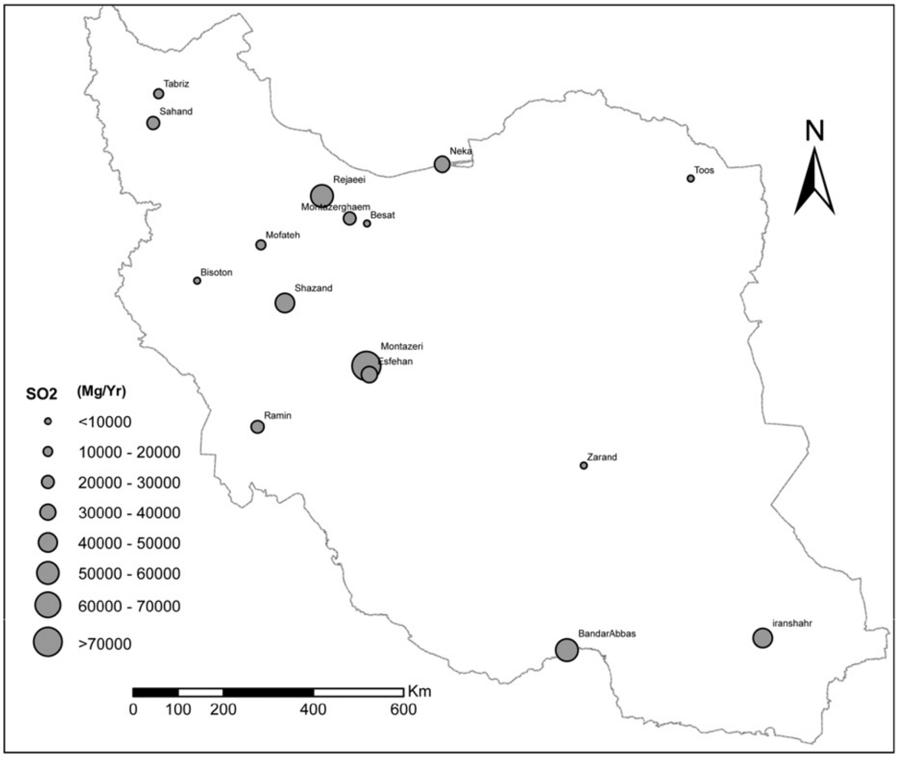

Fig. 4. SO_2 emissions from Iran's steam power plant in 2007 (adopted from Developing Pollutant Map of Iran's Thermal Power Plants (2008)).

Table 6
SO_2 dispersion from Iran's steam power plants based on ADMS software outputs (adopted from Developing Pollutant Map of Iran's Thermal Power Plants (2008).

No	Power plant	Concentration of SO_2		
		Annual ($\mu g/m^3$)	Maximum 24-h ($\mu g/m^3$))	Maximum 3-h ($\mu g/m^3$)
1	**Besat**	4	147	713
2	**Isfehan**	12	247	926
3	**Montazarghaem**	14	478	2320
4	**Zarand**	11	139	613
5	**Neka**	7	323	1399
6	**Ramin**	3	140	662
7	**Bandarabbas**	34	293	1065
8	**Montazeri**	6	295	1023
9	**Toos**	3	302	1830
10	**Tabriz**	13	723	4887
11	**Rajaeei**	12	1967	4817
12	**Bistoon**	8	372	2280
13	**Hamedan**	3	178	578
14	**Iranshahr**	33	246	1019
15	**Shazand**	4	469	1194
16	**Sahand**	3	301	2401

pollutant exiting Iran's steam power plants (Developing Pollutant Map of Iran's Thermal Power Plants, 2008).

6.2. Dispersion of sulfur dioxide around Iran's heavy oil-fired steam power plants

Maximum SO_2 concentration around under-study power plants in terms of $\mu g/m^3$ is represented in Table 6. As shown in Table 5, according to primary and secondary air quality regulation of Iran, valid limit of SO_2 annual concentration is not exceeded in any of heavy oil-fired steam power plants under study because 14 of these power plants (except for Zarand and Iranshahr power plants) consume natural gas in some seasons such as spring and summer. Based on ADMS calculations, annual environmental intensity of SO_2 exiting steam power plants is lower than the limit value determined by primary and secondary clean air standards of Iran. Low installed capacity in Zarand (40 MW) and an Iranshahr (256 MW) power plant leads to the reduction of SO_2 emission rate (1201 and 5623 kg/h in turn). It should be mentioned, the less emission rate of SO_2, the less dispersion concentration of SO_2 (Developing Pollutant Map of Iran's Thermal Power Plants, 2008).

On the basis of secondary air quality regulation of Iran, 24-h SO_2 concentration is valid in Besat, Ramin, Iranshahr, Zarand, Hamedan and Isfehan power plants and 3-h SO_2 concentration is only valid in Besat, Shazand, Hamedan, Ramin, Iranshahr, Bandar-Abbas, Zarand and Isfehan power plants. These observations can be resulted by topographic conditions of the area, flatness of the areas on which power plants are established and low capacity of some power plants (such as Zarand and Iranshahr). In general, mountains and uneven areas around a power plant result in the accumulation of pollutant intensity in the region, which leads to the increase of SO_2 concentration. In addition, pollutants do not dilute in the atmosphere in autumn and winter due to very low mixing height (Developing Pollutant Map of Iran's Thermal Power Plants, 2008).

Inversion phenomenon can also intensify the influence of surface characteristics. For instance, 24-h and 3-h limits based on the secondary standard are exceeded in Tabriz, Bistoon and Sahand power plants since the areas in which they have been constructed are mountainous. Considering the development plan of Bistoon steam power plant, further utilization of heavy oil to generate electricity will cause serious damages to urban and rural regions and natural resources around this power plant because 24-h and 3-h air quality regulations are not respected in the area. Thus, in addition to technical requirements, region acceptance potential, respecting environmental and residential issues, have to be considered in positioning phase of power plant development or construction plans so that urban and rural regions and natural

resources are protected from damages caused by gaseous pollutants, particularly SO_2 (Developing Pollutant Map of Iran's Thermal Power Plants, 2008).

7. Discussion: comparison of SO_2 emissions in Iran's heavy oil-fired steam power plants with their alternatives in Turkey and China

The average emission factor of SO_2 pollutant in Iran's heavy oil-fired steam power plants was 15.27 g/kWh, which means regarding the amount of electric energy generated by steam power plants using heavy oil, 541,000 Mg of this pollutant was produced (Developing Pollutant Map of Iran's Thermal Power Plants, 2008).

The strategies for reducing SO_2 emissions from heavy oil-fired steam power plants can be classified into three groups (Al-Gharib et al., 2007):

– Fuel switching from heavy oil to natural gas.
– Sulfur content reduction of heavy oil fuel.
– Installation of Flue Gas Desulfurization (FGD) systems.

One of the simplest ways to reduce the amount of SO_2 emissions can be achieved by switching to a fuel, which has lower sulfur content. Considering Iran's position as the second reservoir of natural gas in the world (992 Trillion cubic feet, 15.9% of the world total), the cost of this method is relatively low. Fuel switching from heavy oil to natural gas is considered to be the best strategy in Iran's heavy oil-fired steam power plants for following reasons:

– Environmental well being
 Using natural gas in substitution to heavy oil, results in the reduction of SO_2 and other pollutants. Heavy oil contains large amounts of sulfur (about 3% mass) while this is insignificant in natural gas. Therefore fuel switching from heavy oil to natural gas will decrease the SO_2 emissions considerably (UNFCCC, 2010).
– Technical well being
 In contrast with a heavy oil-fired steam power plant the total energy consumption in a natural gas-fired power plant is lower. This is because gas firing requires less excess air and no steam for atomizing the fuel, and the flue gas is discharged at a lower temperature. With natural gas firing, higher efficiency and higher heat transfer rates can be maintained due to lower deposits on the boiler tubes. Fuel ash corrosion and sticky ash deposition on the tubes of the superheater and economizer do not occur in natural gas firing. In contrast with a heavy oil-fired steam power plant the maintenance cost f or a natural gas-fired power plant is less. Typically 28.6–37.5% (Al-Gharib et al., 2007).

The reduction of the amount of sulfur normally found in fuel, particularly in crude oil and in heavy fuels is complicated and expensive, especially for Iran. According to the report of Iran's Ministry of Energy, the cost of desulfurization amounts to 7 US$ per barrel (0.158 m^3) for fuel oil (Rostamihozori, 2002). Therefore the cost of using low sulfur fuels in Iran's heavy oil-fired steam power plants considering the total heavy oil consumption in 2007 (Table 3) is equal to 373.7 million US$. Another strategy for reducing SO_2 emissions in Iran's steam power plants is installation of Flue Gas Desulfurization plants in the existing and new power plants. An appropriate FGD system is selected on the basis of the size and load pattern of the plant, the SO_2 concentration and required reduction level, the availability of the absorbent and possible disposal or utilization of the end product (Al-Gharib et al., 2007). The capital cost for installation of FGD systems in Iran's heavy oil-fired power plants considering the control cost (85% removal efficiency) for SO_2 reduction in these power plants (1053 US$/ton SO_2) will be equal to 569.6 million US$ (Cofala et al., 2004).

Turkey's installed power capacity in 1987 was 12.4 GW, which increased more than three times in 20 years, and was 40.8 GW in 2007. Turkey generated about 190 TWh of electricity in this year. Nearly 70% of electricity generated during 2007 in Turkey based on fossil-fuel combustion. Natural gas (53.69%) is the largest source of fuel for electricity generation followed by lignite (30.07%), hard coal (9.63%) and fuel oil (6.42%).The total sulfur content in Turkish lignite is various depending on the region of the deposits (0.6%–4.5%). In Turkey, 13 large-scale power lignite-fired power plants are responsible for generation of electricity (47.97 TWh in 2007). 8 lignite-fired power plants were equipped with the Flue Gas Desulfurization system. The average emission factor and the SO_2 emissions in these power plants were calculated as 7.68 g/kWh and 368432 Mg, respectively, in 2007 (Vardar and Yumurtaci, 2010).

Turkey considers a pilot emission trading system for SO_2 and other pollutants emitted from its coal and lignite fired power plant in the efforts to comply with the EU Integrated Pollution Prevention Control (IPPC), the Large Combustion Plant (LCP) and the National Emissions Ceiling (NEC) Directives. Turkey has started the screening of the relevant Directives, and formal negotiations with the EU on the environmental chapter are expected to start early 2007. Model calculations indicate that this could yield substantial cost savings compared to a traditional command and control approach. However, requirements in the IPPC Directive would be a major obstacle against emissions trading. The Turkish emission permitting system needs a major overhaul, including improving monitoring and enforcement practices to comply with the Directives and to be able to implement and operate as an emission trading system. All coal and lignite fired power plants that should stay in operation would have to install Continuous Emission Monitoring systems (CEMs) of several pollutants (SO_2 and other pollutants) in the future to comply with the LCP Directive (ECON, 2006).

Recognizing these issues, the Turkish federal government and municipalities have taken several measures to reduce pollution from energy sources. In order to meet EU environmental standards, Turkey is requiring Flue Gas Desulfurization (FGD) units on all newly commissioned coal power plants and is retrofitting FGD onto older units. In addition, the planned ''Blue Stream'' natural gas pipeline from Russia should provide the necessary supplies for Turkey to rely more heavily on cleaner-burning gas rather than coal (U.S. DOE, 2000).

Coal-fired power plants are responsible for generation of electricity (2913.1 TWh in 2009) (IEA, 2009a, b) in China. According to the related research, the sulfur content of the raw coal in china was 1.05% (Di et al., 2007). The average emission factor of SO_2 and its emission (in 2005) in these power plants were estimated to be 8.22 g/kWh and 16,097,000 Mg, respectively. In 2007, China's coal-fired power plants produced 2533.02 TWh (77.7% of total electricity generation) (U.S. DOE, 2009). The average emission factor of this pollutant and its emission in this year were calculated to be 5.65 g/kWh and 14,330,000 Mg, respectively (Su et al., 2011). SO_2 emissions would decrease to 11,801,000 Mg in 2010 attributed mainly to the wide application of the Flue Gas Desulfurization system (FGD) (Zhao et al., 2008). To achieve this goal, FGD devices are now being widely installed in coal-fired power plants. In 2005, only 15% of the power plants had FGD. By 2009, the percentage has increased to 71%. Considering that all newly-built power plants will install FGD, and

Table 7
Average emission factor of SO_2 and the emission of it in Iran's steam power plant in comparison with Turkey and China (adopted from Developing Pollutant Map of Iran's Thermal Power Plants (2008), Vardar and Yumurtaci (2010), Zhao et al. (2008), Su et al. (2011)).

Country	Electricity generation (TWh)		Emission factor (g/kWh)	Emission (Mg)
Iran (2007)	Heavy oil	35.49 (17.4%)	15.27	541000
Turkey (2007)	Lignite	47.97 (30.07%)	7.68	368432
China (2005)	Coal	1956.2 (78%)	8.22	16097000
China (2007)	Coal	2533.02 (77.7%)	5.65	14330000

some of the older plants will be retired, the percentage will continue to increase during 2010–2020 (Xing et al., 2011).

The Chinese government has attached great importance to the control of SO_2 and has adopted a series of control measures. These measures include the designation of "two control zones" (one focused on high levels of acid precipitation and the other on high ambient SO_2 concentrations) and a pollution levy fee on SO_2 emissions. In addition to these measures, China has formulated a set of technology policies related to SO_2 emissions, such as restricting the use of high sulfur-content coal, requiring coal washing, and employing Flue Gas Desulfurization. The cornerstone of recent Chinese air quality policy is the Total Emissions Control (TEC) program. The TEC program specifies a national SO_2 emission target and allocates the target to the provincial and municipal levels. China's "Tenth Five-Year Environmental Protection Plan" set the TEC limit at 10% below 2000 emissions levels nationwide and 20% below 2000 levels in the two control zones. These reductions must be met during the Tenth Five-Year Plan period (2001 to 2005). The structure of the TEC policy, which includes setting national emissions limits, could form the foundation for a "cap and trade" program. A strictly managed total cap on emissions is a necessary element for an emissions trading program, and an effective cap will ensure that the environmental goal is met. The use of emissions trading helps ensure that emission reductions are made cost effectively, since trading encourages reductions where they are least costly. Experimentation with pilot projects in the 1990s gave China some experience with the potential benefits of emissions trading. Total emissions control, improved management capacity, a maturing market and requirements on environmental quality all seem to suggest China should formally embrace emissions trading (EPA, 2002).

As shown in Table 7, it is apparent that the average emission factor of SO_2 in Iran's steam power plants having no Flue Gas Desulfurization system (FGD) and no emission control program for emission reduction of this pollutant is more than the emission factor of this pollutant in Turkey's and China's thermal power plants. The best way to reduce emission factor of SO_2 in Iran's steam power plants can be achieved by switching heavy oil to natural gas. Decreasing 1% of heavy oil consumption (in 2007) in Iran's heavy oil-fired steam power plants is resulted to SO_2 emissions reduction equal to 37869.6 Mg. The capital cost of Flue Gas Desulfurization (FGD) systems for this amount of SO_2 emissions control is approximately equal to 40 million US$. However the fuel cost (0.0615 US$/$m^3$) of increasing 1% of natural gas consumption (in 2007) in Iran's heavy oil-fired steam power plants is approximately equal to 5.4 million US$ (Developing Pollutant Map of Iran's Thermal Power Plants, 2008).

8. Conclusions

Iran's steam power plants use heavy oil as a secondary fuel. Sulfur percentage of this fuel consumed in Iran's power plants ranges from 1.55 to 3.5. This material results in the production of SO_2 pollutant, which depending on atmosphere endurance and region topography disperses in the atmosphere and causes destructive damages to human health, buildings and habitations and also power transmission and distribution lines and power plant equipments. Based on the energy balance books of Iran, social cost of the production of this pollutant in power plant sector of Iran was equal to 683 million US$, equivalent to 2.6% of Gross Domestic Production of Iran, in 2007 (Central Bank of Iran, 2007; Energy Balance Book, 2007).

The social cost of SO_2 emissions from Iran's steam power plants is more than the capital cost for installation of FGD systems (569.6 million US$) and the cost of using low sulfur fuels (373.7 million US$). Therefore, endurance, control and reduction of dispersion amount of this pollutant in Iran's steam power plants are of crucial importance. On the other hand, positioning new power plants and considering region acceptance for developing the existing units are feasible by modeling gaseous pollutants dispersion using common methods (Receptor and Source Oriented Models). Conclusions achieved in this study are briefly as follows:

- Emission factor of SO_2 pollutant exiting steam power plants utilizing fuel oil is equal to 15.27 g/kWh. Emission amount of this pollutant produced by steam power plants was 541,000 Mg in 2007. Nevertheless, maintaining the current condition of steam power plants and ignoring sulfur dioxide reduction systems will lead to the increase of SO_2 emissions in electricity generation regarding the development of steam power plants in this sector.
- Absence of the Flue Gas Desulfurization Systems (FGD) in Iran's steam power plants and existence of high sulfur content (about 3% mass) in heavy oil as well as the fact that 17.4% of the generated power using heavy oil is not substituted by natural gas lead to SO_2 emissions from Iran's steam power plants.
- The average emission factor of SO_2 in Iran's steam power plants having no Flue Gas Desulfurization system is more than the emission factor of this pollutant in Turkey's and China's thermal power plants.
- More fuel oil consumption in steam power plants particularly in cold seasons increases the dispersion of SO_2 pollutant in the atmosphere and accumulation of SO_2 concentration around the power plants due to low mixing height and temperature inversion phenomenon. This finally results in exceeding Iran's air quality regulations.
- Substitution and utilization of renewable energies such as hydroelectric, wind, solar, geothermal and biomass energies reduce the dispersion of SO_2 and other pollutants exiting Iran's power plants. It is planned to generate 5.24% of total power demand of this country using nuclear energy in 2025.
- Iran's Department of Environment has to enact new laws and regulations in order to stabilize, reduce and control gas pollutants like SO_2 proportional to climatic conditions and region acceptance potential regarding the reception of pollutants exiting power plants.
- Enacting tax laws (tax on emission) or encouraging and protecting policies with respect to pollution dispersion level can lead to the utilization of new systems and technologies in order to reduce pollutants such as SO_2.
- Utilization of Continuous Emission Monitoring (CEM) to measure SO_2 exiting steam power plants can influence the reduction of SO_2 emissions using FGD systems.
- Allocation of new steam power plants regarding technical and environmental issues can reduce damages caused by the increase of SO_2 pollution load exposed to the environment.

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